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MEASUREMENT OF MUON ENERGIES OF 1-2 TeV AND ABOVE IN THE DUMAND DETECTOR*

Arthur Roberts

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by

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ABSTRACT

In the deep ocean, the only method available for the measurement of the energy of muons of 1-2 TeV and above is the measurement of dE/dx. It is shown that Cerenkov detectors will receive signals adequate for these purposes at distances up to 30 - 40 meters from the muon track. Signal processing strategies are considered, and are shown to reject K^{40} background adequately. Energy resolution of 25 - 35% has previously been claimed; further work on detailed detector configurations is required.

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The initial proposal for DUMAND[1] envisages a search for the manifestation of the intermediate vector boson (IVB) in high-energy neutrino-nucleon inelastic scattering in the y-distribution, which should change markedly as the cm energy passes through the IVB mass range (see, e.g. Gaisser and Halprin[2].) In order to measure the y-distribution it is necessary to measure the direction and energy of both the nucleonic cascade produced, and the high-energy muon emitted in the interaction.

Measurement of the cascade energy and direction is possible both by detection of the Cerenkov light emitted[3] (optical detection) and by the acoustic pulse emitted at sufficiently high energies[4], which has been experimentally studied[5]. In the ocean magnetic analysis is not feasible, and the energy measurement of the emitted muon must be via the rate of energy loss. Such a measurement does not seem to be feasible by acoustic methods, however, except possibly at extremely high energies (ca 1000 TeV.) Recourse to measurements via Cerenkov radiation will be necessary.

Since a path length of a few hundred meters or more should be available, reasonably good averaging of the energy loss in this distance should be possible. The threshold for measurements by this method is on the neighborhood of 1-2 TeV (see Fig. 1); below that energy the radiation losses are not sufficiently dominant. Borog et al[6] have already considered this problem and estimated that accuracies of 25 to 50% should be attainable; such accuracies are adequate for the purposes of the y-distribution experiment.

In the ocean the distance to which the Cerenkov radiation from the fast muon can be detected will depend on both the water transparency and the rate of energy loss, the latter determining the track luminosity. Fig. 2 shows the effect of light absorption in water on the spectrum of the Cerenkov light, and Fig. 3 the light intensity as a function of distance from the muon track, ignoring the fluctuations and assuming a uniform intensity. In Fig. 3, the water absorption has been included. In order to estimate the usable distance two additional factors are required: the threshold light intensity required for reliable detection and the light attenuation length in the water.

The threshold light intensity feasible for detectors in the ocean has been the subject of considerable study; it is of the utmost importance that this quantity be reduced to a minimum. We presently consider a usable threshold level to be around 100 quanta/m^2, in the blue-green region of greatest water transparency. This value is base on a specific conceptual design for the light sensor, which is shown in Fig. 4. The light sensor consists of a transparent tube containing a solvent in which the wavelength shifter is dissolved. The refractive index of the solvent is as high as can be arranged, consistent with the necessary properties of wavelength-shifting and of transparency to the shifted light. An example of the values desired might be: index of refraction 1.50 or above, wavelength of reradiated light about 550 nm, attenuation length of solvent at 550 nm 3m or more.

Triggering level. - In order to calculate the required incident light flux we need to define the triggering conditions more exactly. For the sake of illustration we select a model like Fig. 4. Let the overall length be 6m, the diameter 0.33m, so that the cross-sectional area presented to a normally incident light beam is 2 m^2. We first investigate the overall efficiency of light conversion, the characteristics of the photomultipliers needed and the effect of the residual light background due to the Cerenkov radiation from the K^{40} naturally present in the ocean.

Efficiency of production and collection of fluorescent light in wavelength-shifter systems. - Let the wavelength-shifter have 100% fluorescent efficiency, a value readily approached. The fluorescent light is emitted isotropically, and the fraction captured by internal reflection in the waveshifting medium is a function of the indices of refraction of the shifter, n_2, and of the seawater, n_1 (=1.33). The fraction of light captured is $f = (n_2 - n_1)/n_2$. For $n_2 = 1.50$, $f = 0.113$. By Liouville's theorem, this is also the minimum fraction of the cross-sectional area of the wavelength-shifter tube that must be occupied by the photocathode, if all the light captured by internal reflection is to be concentrated on it by mirrors, assuming no further wavelength shifting. Thus in the example given, the photocathode must have an area $.113 \times \pi \cdot 16.5^2 = 97$ cm^2, corresponding to a nominal 5-inch diameter.

The wavelength-shifted light will suffer absorption in the solvent in travelling to the PMT detectors; if the attenuation length for the fluorescent light is L_o, the overall length of the sensor L, the fraction of the fluorescent light emitted in the allowed cone that reaches each end is $\frac{1}{2}L_o/L \times (1 - \exp(-L/L_o))$. For the case L = 6m, L_o = 4m, this is 0.26. If we assume an incident light flux of 100 quanta/m^2, we find about 6 quanta reaching each PMT cathode, for an average signal of about 1 photoelectron.

Signal Processing. - The most obvious method of treating the signals would be to require a coincidence between the two PMT tubes of each sensor. But to reach a coincidence efficiency of detection of 90% would require each PMT to be 95% efficient, and thus to produce an average of 3 photoelectrons. This would require an incident light flux of 300 quanta/m^2.

We can do much better if we note that there will be many sensors exposed to the light from a single muon, and thus in time coincidence (within time-of-flight limitations.) Thus, suppose there are 20 PMT's exposed to the signal, each with an average of 6 photons, yielding on the average 1 photoelectron. The individual PMT efficiency will be .635, and the most probable number of PMT's simultaneously firing will be 12.7. Even if we demand 2 photoelectrons for a trigger, the most probable number of PMT's firing will be 5.2, well above the noise.

Background from K^{40}. - If we contemplate setting trigger levels at one photoelectron, the omnipresent K^{40} background must be considered. The ocean potassium content gives rise to 13 disintegrations/liter sec, and an estimate of 55 Cerenkov quanta per average disintegration , with the usual 20m-attenuation length for light, yields an estimated flux of Cerenkov light of 500 quanta/cm^2 sec, or 5×10^6/m^2 sec. If we assume the same detector configuration as for the muon signal, we find about 3×10^5 quanta/sec reaching each PMT cathode, and thus a background rate of about 6×10^4 sec^{-1}, of which the vast majority (over 98%) are single-photoelectron counts. This is sufficiently small that random background effects can readily be eliminated by almost any sort of coincidence system. Thus, with the background rate specified as above, if we ask for the random coincidence rate among any 2 of 20 PMT's, the random rate will be one count every 1600 sec. If we demand a fivefold coincidence, corresponding to the average number of tubes triggered by a photon flux of about 40 photons/m^2, the background rate will be one count every four months. A 25-nsec resolving time was assumed.

Summary. - We see that it appears plausible to detect photon fluxes of 100/m^2 or perhpas even less. The nominal values assumed in the above calculations have not been attained in the laboratory at the wavelengths specified; but they do not appear to be unreasonable. From Fig. 3 we can see that even at 6 TeV (10x minimum ionization average density) muon tracks will be observable at distances up to 30-40 meters away, so that the required density of sensors will remain quite modest, and comparable with that required for cascade energy measurement.

Energy Measurement. - While previous work[6] has shown that measurements of energy to 25 - 35% should be possible, detailed studies of the dependence of this accuracy on sensor configuration and density have not as yet been carried out. This should be the next stage of the study.

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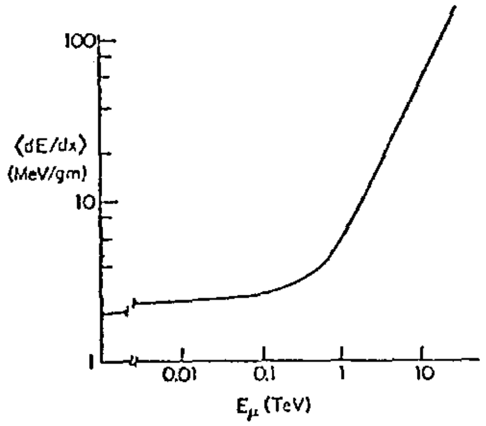

Fig. 1. Energy loss of fast muons in water. Above ca 1 TeV the rate of energy loss is proportional to energy, and is primarily radiative. Muon energy may be determined from dE/dx.

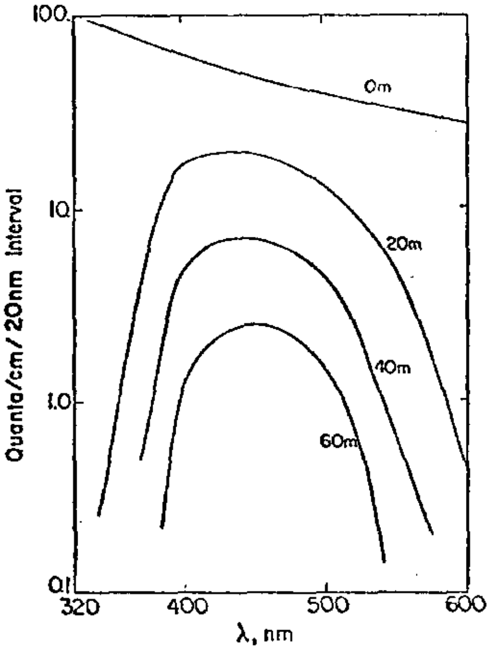

Fig. 2. Attenuation of the Cerenkov spectrum by seawater. The attenuation length is assumed to be 20m at 460 nm. Intensity is given in number of quanta radiated per cm per unit wavelength interval. The curves show the specrum after 0, 1, 2, and 3 attenuation lengths, respectively.

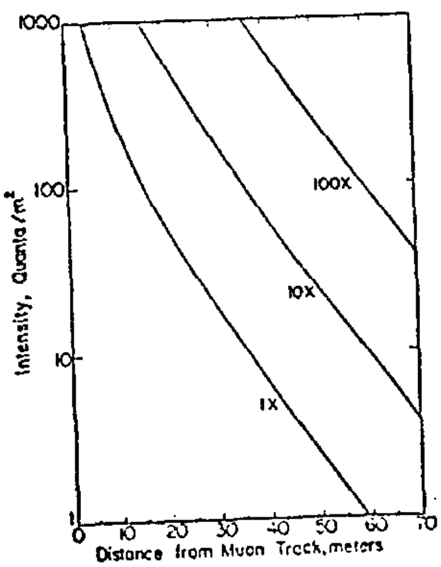

Fig 3. Intensity of Cerenkov light as a function of radial distance from a muon track of 1, 10, 100 x minimum ionization respectively; these correspond to energies of 0.1, 6., and 60 TeV respectively. Detection threshold is in region of 100-200 quanta/m^2.

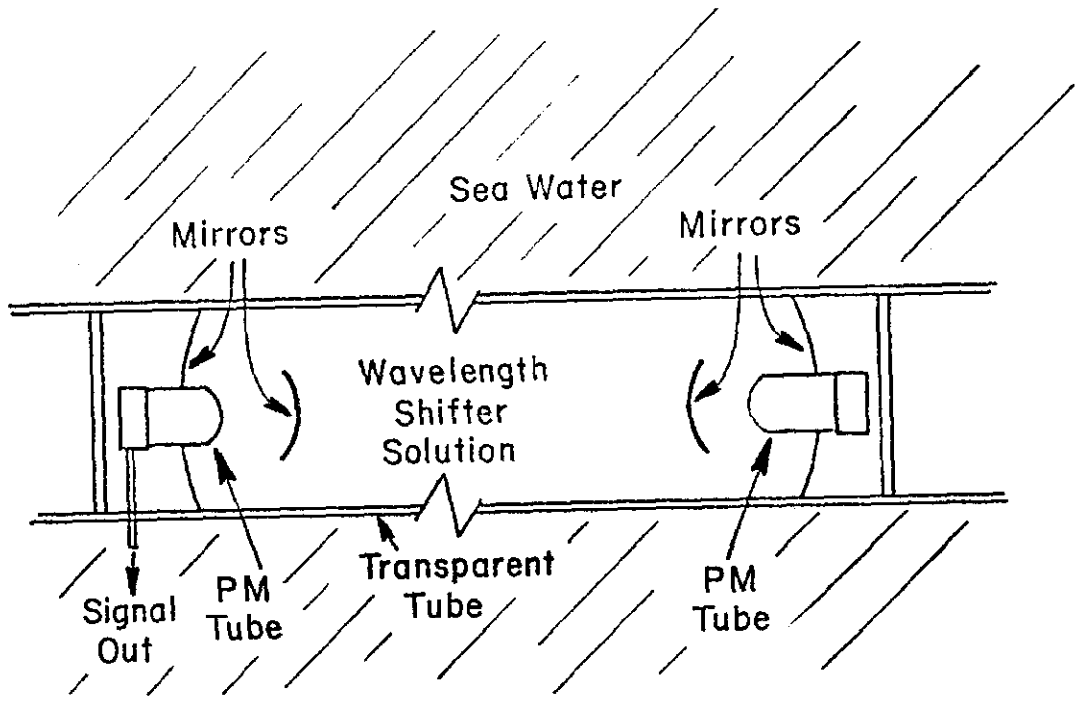

Fig. 4. Conceptual sketch of light sensor unit using wavelength shifting technique. The mirrors indicate schematically a possible light-collection technique. The entire assembly operates at ambient pressure. In the example used in the text, the PMT's are 5" diameter, the transparent tubes 33 cm, and the length of one unit is 6 m.